APPENDIX F

Accelerator Science and Technology
in Support of Office of Energy Research Programs

Particle accelerators are the tools that support a significant component of the research programs overseen by the Office of Energy Research (OER). As such, advances in the research missions of OER are strongly coupled to advances in accelerator physics and technology. Over the years this reliance has been recognized, and accelerator R&D in support of OER missions has been an important component of the programs of the U.S. Department of Energy (DOE) and its predecessor agencies. This appendix reviews the underlying accelerator technology base supporting OER's research programs and identifies the technologies that will be required to support a continuation and expansion of research opportunities into the future.

High Energy Physics

High energy physics (HEP) research is aimed at identifying and understanding the most fundamental building blocks of matter and the forces that govern their behavior. HEP operates at the high energy frontier. The Tevatron currently operates at 1800 GeV in the center-of-mass, making it the highest energy collider in the world today. The Stanford Linear Collider (SLC) operates at 90 GeV, making it, along with the Large Electron-Positron Project (LEP) machine at the European Laboratory for Particle Physics (CERN), the highest energy electron colliders in the world. The goal of the HEP community over the next few decades is to advance the energy and luminosity capabilities of the collider facilities by at least an order of magnitude.

Current Accelerator R&D

The accelerator R&D program in support of HEP has been largely effective in addressing needs in the near to intermediate term future. Major achievements associated with this program over the past 20 years include, but are not limited to:

- Development of high luminosity electron-positron storage ring colliders
- Development of the first synchrotron/storage ring based on superconducting magnets
- Development of the first electron-positron linear collider
- Development of superconducting materials capable of supporting current densities of >3000 A/mm^2 in an accelerator magnet application
- Development of rf sources and structures capable of supporting accelerator gradients of 50 MeV/m or more
- Development of high bandwidth (up to 8 GHz) stochastic cooling
- Development of an antiproton source capable of supporting high luminosity proton-antiproton collisions.
- Development of polarized proton sources and means for preserving polarization during acceleration
- Development of polarized electron sources to support high-luminosity operation in a linear collider
- Development of concepts for medium energy electron cooling
- Development of techniques for measurement of wakefield (or impedance) characteristics of accelerator components up to and beyond the GHz range
- Significant contributions to the field of non-linear dynamics.

These developments have allowed the U.S. HEP program to remain at the forefront of research worldwide. Effectiveness of the program results largely from recognition and acceptance on the part of the HEP laboratories, the DOE (and National Science Foundation [NSF]) program offices, and (most importantly) the user community of the ongoing need for both directed and more generic accelerator R&D to provide the tools needed to ensure the continued health of the field. This recognition and acceptance has led to the commitment of significant resources by each of the HEP laboratories plus the proposal-driven, peer-reviewed program administered by the DOE HEP office that supports long-term accelerator R&D at the universities and HEP laboratories. That program also provides funds for accelerator schools, which have become a major training ground for accelerator scientists and engineers. This training, plus many of the advances in accelerator science and technology supported by the HEP programs, have formed the basis for the development of forefront facilities in the other OER programs.

Fermi National Accelerator Laboratory (Fermilab), Stanford Linear Accelerator Center (SLAC), and Cornell are all currently engaged in significant upgrades to their facilities. The Main Injector project at Fermilab is designed to support a factor of five increase in the luminosity in the Tevatron Collider. At SLAC, the Positron-Electron Project (PEP-II) B-factory is currently under construction and is targeted at observation of CP violation in the B-system. A luminosity upgrade at the Cornell facility is also aimed at enhancing research capabilities in the B-system. Significant R&D programs have been associated with these projects, which are all scheduled to come on-line in the 1998-99 period.

More forward looking mission-directed research is also being conducted at the DOE HEP accelerator facilities. Fermilab is developing plans for enhancements to their antiproton production facility and is in the process of reconstituting a superconducting magnet development program. The medium-term goal is to achieve a luminosity of $\sim 10^{33}$ $cm^{-2}sec^{-1}$ in the Tevatron. A key component of the superconducting magnet effort is the development of superconducting components for the Large Hadron Collider (LHC) program in Europe in collaboration with Brookhaven National Laboratory (BNL) and Lawrence Berkeley National Laboratory (LBNL). This work is being targeted toward areas that are of potential long-term use to the U.S. program.

A significant effort, centered and coordinated at SLAC, is aimed at developing the technology required for a next generation linear (e^+e^-) collider. The short-term goals are to validate requisite technologies and to produce a conceptual design for a facility operating at 500 GeV (center-of-mass), upgradable to 1500 GeV. Other national laboratories and universities are contributing significantly to this program. A novel idea that has resurfaced recently, the muon collider, is receiving serious attention at Fermilab and BNL. Both Fermilab and BNL are also investing some modest effort towards the understanding of issues related to a very large (multi-tens of TeV) hadron collider that could be a candidate for construction following completion of the LHC.

A variety of more exploratory accelerator research investigations are taking place, supported by DOE, at a variety of laboratories and universities around the country, including research into new accelerator and acceleration concepts, superconducting magnet and materials development, high-power rf sources, high-brightness sources, polarized beams, plasma lenses, and space-charge dominated beams. Both experimental and theoretical investigations are supported.

R&D Needed to Support Future Requirements

A number of "enabling technologies" are intimately related to the performance of HEP facilities, and continuing advances in these technologies are required to ensure the continued health of the field. Superconducting magnets are the enabling technology for proton-proton (and proton-antiproton) colliders. Ever increasing energies will be dependent on the development of higher performance magnets. Given the immense size of high energy hadron colliders, the R&D challenge is not only to develop magnets capable of operating at fields approaching 10 Tesla, but also magnets designed to be fabricated and operated at a significantly reduced unit cost relative to current practice.

High-power rf sources and efficient high-gradient rf structures are the enabling technology for electron linear colliders. An intermediate goal is the development of effective accelerating gradients in the vicinity of 100 MV/m. Reduction of fabrication costs and associated operating costs is an important development goal.

A number of next-level technologies remain critical to further advances in hadron and electron colliders. Advances in antiproton production, beam cooling, targeting, beam stabilization, and understanding non-linear effects are all required for both short and long-term advances in hadron colliders. Non-linear optics, beam control, instrumentation, and feedback, are all areas in which advances are required to fuel continued advances in e^+e^- colliders.

More forward-looking R&D is also essential to the continuing health of the field. Investigations, both experimental and theoretical, into new novel collider types, such as muon or gamma-gamma colliders, and new acceleration techniques are examples. While by their nature there is no guaranteed pay-off from any of the areas being investigated on an individual basis, history teaches that it is likely that fundamental developments significantly impacting the future of HEP are likely to emerge.

This was reinforced by the 1980 HEPAP Subpanel chaired by M. Tigner which reviewed accelerator R&D and looked at the future of accelerators and colliders. The Tigner Panel recommended that about 4% of the DOE high energy physics operating budget be dedicated to long-term R&D, beyond the immediate needs of the laboratories. Although this funding level has not been fully reached, the goal led to the establishment of a separate effort within the DOE high energy physics program for long-term R&D. This program funds research groups at the national laboratories, at universities and in industry, and provides the main support for training graduate students in accelerator physics. Some of the significant contributions resulting from this program include:

- Research at the University of Wisconsin led to a basic understanding of the flux-pinning mechanism in NbTi superconductors, which produced a 50% increase in the short-sample limit. This improvement in performance is critical for high energy hadron colliders. In addition, these improved superconductors have found wide use in high-field magnets in many fields such as Magnetic Resonance Imaging (MRI) scanners and insertion devices for synchrotron radiation.

- Nonlinear dynamics and classical physics research at the University of Maryland led to widely used applications of Lie algebra in computing nonlinear lattices. There have also been important theoretical contributions to electromagnetic field computations, impedance calculations, beam-breakup physics, beam halo formation, and design of permanent magnet optics.

- Research on alternate methods of acceleration with very high peak power lasers has generated accelerating gradients in excess of 1 GeV/m over small distances. These gradients are well beyond the capability of existing technology and could lead the way to very high energy accelerators in the future.

- The U.S. Particle Accelerator School, founded as a result of the Tigner Panel, has trained accelerator scientists who have gone on to contribute to accelerator-based projects within all five OER programs, as well as to the projects of other agencies.

Nuclear Physics

Nuclear physics research is conducted to understand, at a fundamental level, the structure and dynamics of strongly interacting matter, its properties under a wide variety of conditions in the laboratory and the cosmos, and the forces that govern its behavior.

Pursuit of this goal entails development of new technologies and advanced facilities, and education of young scientists.

The centerpiece facilities of the nation's nuclear physics program are the Continuous Electron Beam Accelerator Facility (CEBAF), which is just coming into operation, and the Relativistic Heavy Ion Collider (RHIC) which is scheduled to begin operations in 1999. Other accelerator facilities include electron, proton, and ion accelerators at a variety of DOE laboratories and those at universities supported by both DOE and NSF for use by nuclear scientists supported by both agencies. Each of these facilities has developed in close association with R&D in accelerator science and technology, particularly short-term R&D. In this section examples are given of the medium-term accelerator R&D that will enable these facilities to remain at the scientific forefront during the remainder of their productive lives as well as the long-term accelerator R&D that will lead to new technologies and new science in nuclear physics with significant spin-off into other areas of science.

Superconducting rf cavities, successfully developed over the past two decades for high-velocity electrons (primarily at Stanford (HEPL), Cornell, and Wuppertal, Germany) and for low-velocity heavy ions (primarily at Argonne National Laboratory [ANL] and State University of New York [SUNY] at Stony Brook) are pushed even further. Based on the former, the accelerator R&D at CEBAF led to the development of reliable high-gradient, high-Q cavities with higher order mode suppression that exceeded design specifications and will permit upgrading the CEBAF energy at small cost. Long-term R&D in this area will likely lead to a further factor of two or so in gradient and will likely open this technology to other applications such as the use of superconducting rf cavities as accelerator drivers for high-power interaction regions (IR) and ultraviolet (UV) free electron lasers (FELs) and, possibly, in high energy linear colliders. On the other end, superconducting heavy-ion cavities are extended down in velocity for important applications with very heavy beams and low-charge state radioactive ion beams.

Beam dynamics studies of high-current, low-emittance beams are essential for understanding wakefields, instabilities, beam breakup, bunch lengthening and emittance growth in order to obtain the most effective beam characteristics for facility performance. In nuclear physics, such studies are needed for the development of polarized electron sources, heavy ion sources, radioactive beams and electron cooling.

The development of high-charge state electron cyclotron resonance (ECR) ion sources is revolutionizing the acceleration of heavy-ion beams both at cyclotrons and heavy-ion linacs. A program of heavy ion source development based on the EBIS technology is underway at BNL for possible use at RHIC. The R&D goals are increasing the intensity and extending the ion species.

The development of polarized gas targets at Wisconsin and of polarized ion sources and _________ polarized target at TUNL has important applications to the research programs at large accelerators and exemplifies the symbiotic relationship between small university accelerators and large national and international facilities.

The use of electron cooling of ion beams has been greatly advanced by recent R&D. In fact, the low emittance of the cooled beam has proved to be an excellent tool to observe non-linear, single-particle beam dynamics effects. The medium-energy electron cooling R&D initiated at the University of Indiana has been carried over to

Fermilab where it is being further developed in support of the design of a new antiproton accumulator ring.

The RHIC accelerator R&D program is focused on superconducting magnet technology, bunched beam stochastic cooling, and implementing polarized beam operation. Among the advances in magnet technology are techniques to measure the magnetic fields and then to correct for deviations from the design values. These will have impact in other accelerator projects worldwide. A viable bunched-beam stochastic cooling system has the potential for ameliorating the effects of intrabeam scattering in heavy ion beams and thus providing a significant performance improvement. A recent decision has been made by the RIKEN Research Institute in Japan to fund both the detector and accelerator modifications needed to implement polarized proton operation at RHIC. This has led to an R&D program to develop so-called Siberian snakes and spin rotators based on a superconducting helical dipole magnet design. In addition, there is an accelerator physics program to develop the tools and techniques needed to analyze spin dynamics.

The National Superconducting Cyclotron Laboratory (NSCL) facility at Michigan State University and the Indiana University Cyclotron Facility (IUCF) are both supported by the NSF. The recent Nuclear Science Advisory Committee (NSAC) long-range plan recommends an upgrade of the radioactive-beam capabilities at Michigan State and support for a Light Ion Spin Synchrotron based on the Indiana infrastructure. The upgrades proposed at both the NSCL and IUCF are based on technologies developed through R&D at those facilities during the past two decades, and funded as part of their on-going NSF nuclear physics research programs.

The NSAC long-range plan also recommends a design study for a next generation ISOL-type (Isotope Separation On-Line) radioactive beam facility based on the two accelerator (driver/post accelerator) concept and its construction once construction of RHIC is substantially complete. The advanced ISOL facility will bring together the fruits of many accelerator developments of RFQ's, conventional linacs, superconducting linacs, and target/ion source systems carried out in recent years at a variety of nuclear physics facilities such as LBNL, Los Alamos National Laboratory (LANL), ANL, and Oak Ridge National Laboratory (ORNL).

Basic Energy Sciences

The Office of Basic Energy Sciences (BES) conducts research in materials and chemical sciences, geosciences and other fields directly related to the DOE energy mission. As part of its program, BES supports the design, construction, and operation of synchrotron light and neutron sources at a number of DOE laboratories. These major user facilities are used by researchers from DOE laboratories, industry, and universities.

Synchrotron Light Sources

Areas of accelerator science and technology that have led to significant improvements in synchrotron radiation source performance are the development of low-emittance lattices, the development of insertion devices, and improvements in orbit and beam control. Low-emittance lattices are accelerator magnet configurations that lead to high brightness beams without deleterious effects. Insertion devices are special magnets that can be designed to give higher energy X-rays than bending magnets, to concentrate the photon beam intensity into narrow energy bands, or to control other photon beam properties such as polarization. The accelerator beam must be stable to unprecedented levels to take advantage of the high brightness beams, and this has led to the development of new instrumentation and feedback techniques.

Developments that could lead to synchrotron light sources with improved capabilities is the subject of accelerator R&D supported by BES. One approach is higher brightness storage rings based on extensions of the storage ring designs used for the Advanced Light Source (ALS) and the Advanced Photon Source (APS). This will require increased understanding and improvement of low-emittance lattices, insertion devices, and beam stability and will be based in large part on the experience gained with the ALS, APS, and other similar synchrotron radiation sources.

The other approach to light sources with advanced capabilities is the Free Electron Laser (FEL). FELs can be based on high brightness storage rings or linear accelerators. Linear accelerator FELs could cover energies from the infrared to X-ray. Infrared FELs have the potential of being of moderate size appropriate to a university or industrial setting; here the accelerator R&D is aimed at lowering the cost of critical elements. FELs for higher energies would be larger and would be multiple user facilities located at a national laboratory. The accelerator science and technology of these larger FELs has considerable overlap with that required for the development of linear colliders for high energy physics: high brightness electron sources must be developed and beams must be accelerated without suffering loss of brightness. In addition, there are R&D issues unique to FELs: the study of self-amplified spontaneous emission and construction of long, precisely aligned undulators.

Neutron Sources

High-current, medium-energy proton accelerators are used to produce spallation neutrons for condensed matter research. The two spallation neutron sources operating in the United States, LANSCE and IPNS, have beam power of 64 kW and 7 kW, respectively.

The development of designs and technologies for spallation neutron sources with beam power in the 1-5 MW range is being considered by BES. The R&D needed for such sources includes producing beams with high current and short pulses, controlling beam halos that can heat up and activate accelerator components, handling high-power deposition in the targets, and developing time-of-flight instrumentation. The first two topics are accelerator-related R&D.

Fusion Energy

The mission of the DOE fusion energy program is to demonstrate the scientific and technological basis for fusion energy. There are two approaches to fusion energy, magnetic (MFE) and inertial (IFE).

Magnetic Fusion Energy

MFE uses strong magnetic fields to confine the energy of high temperature (~10 keV), low density (~10^{20} particles m^{-3}) plasmas for long times (~ several seconds) thereby achieving a net energy production. Accelerators impact the MFE program through their extensive use in neutral beam heating systems and in the future as the source for neutrons in an International Fusion Materials Irradiation Facility (IFMIF). High-power neutral beams based on positive ions accelerated to about 100 keV were developed in the late 1970's, primarily for the Tokamak Fusion Test Reactor (TFTR), and are used extensively in the world fusion program to heat Tokamak plasmas. Development of this technology was terminated in the United States. R&D is being carried out primarily in Japan and Europe and is focused on the production of beams of negative ions accelerated to about 1 MeV.

The IFMIF will use a high-intensity (125-mA), modest-energy (35-MeV) deuteron accelerator to bombard a flowing lithium target to make a high-intensity neutron source with a spectrum and fluence simulating that from a fusion reactor. Candidate materials for an MFE reactor first wall and blanket will be exposed to the neutron flux up to fluences expected over the operating life of the fusion reactor. Currently an international design team from Europe, Japan, Russia and the United States is carrying out a conceptual design study of IFMIT. R&D is planned to be part of the IFMIF project with key R&D efforts focusing on developments needed to produce high-current continuous-duty beams with very low beam loss and high (>90%) reliability and availability.

Inertial Fusion Energy

IFE uses a repetitive short-pulse (~10-ns) intense (~ 10^{14} -watts/cm^{2}) ion or laser beams to compress a fusion fuel pellet that would then produce more fusion energy than was needed to produce the beam. OER is supporting the development of heavy ion induction accelerators as drivers for this application.

Heavy ion fusion requires a 10-GeV high-current (~ 10 kA) ion beam resulting in about 5 MJ/pulse delivered to a fusion target. The primary development path for accelerator-based inertial fusion drivers in the United States involves advanced induction linac accelerators. Complementary development is being carried out in Europe on an approach using an rf accelerator and multiple accumulator rings.

The principle R&D issues for heavy ion fusion drivers are related to maintaining high beam quality during beam manipulation and in the presence of space-charge effects.

There is important synergism between basic plasma science and the advanced accelerator science needed for fusion energy applications of accelerators. For example, the quantitative assessment of collective effects in high-intensity accelerators has its foundation in plasma theory and in computer models developed by the fusion energy program.

Although theoretical modeling related to these issues is well advanced, experimental confirmation has been limited. Major accelerator topics that need to be experimentally confirmed at the appropriate scale are: beam merging with low degradation of emittance, transition from electrostatic to magnetic focusing, low-cost fabrication of induction modules, and beam neutralization in the drift space between the accelerator and the fusion target.

Health and Environmental Research

DOE's Office of Health and Environmental Research (OHER) has as its overarching scientific goal the understanding and technological solution of major problems in biology, medicine, and the environmental sciences as related to energy use and development. Although many OHER programs use accelerators to some degree to address these problems, the most substantial use is in the structural biology and nuclear medicine programs.

Structural Biology

For structural biology, the use of X-ray crystallography to obtain structural information about complex biological molecules drives OHER's interest in beamlines and infrastructure at the nation's synchrotron light sources. There is also OHER interest in X-ray microscopy and spectroscopy, as well as angiography, at synchrotron sources. Neutron scattering is also of interest to structural biology, especially for determining the location of H atoms.

R&D supported by the structural biology program is not directed at accelerator issues; it is primarily directed towards detectors and other instrumentation for X-ray (synchrotron sources) and neutron (reactor and spallation sources) applications, but also includes some development of software systems for data acquisition and beam line management.

Nuclear Medicine

OHER's nuclear medicine program currently supports a modest program of accelerator-related R&D. An upgrade of the Brookhaven Linac Isotope Facility includes a modest amount of accelerator R&D. A project is also underway at the Biomedical Research Foundation at Louisiana State University to develop a prototype $^{3}He^{++}$ RFQ-based system for production of PET isotopes.

In nuclear medicine development of new target designs for the efficient production of radioisotopes at accelerators is a priority. In most cases, emphasis is on modeling of heat transfer properties; however, for the RFQ-based facility the major issues relate to understanding how $^{3}He^{++}$ targeting can effect chemistry changes at high rates.

There is also growing interest in Boron Neutron Capture Therapy (BNCT) now undergoing clinical trials at BNL and MIT. If BNCT is demonstrated to surpass the efficacy of conventional cancer therapy, accelerator-produced neutron beams may be an alternative to reactor-based treatments. This technique is likely to be based on RFQ or electrostatic tandem technology and requires ~1 mA of protons at 3-5 MeV.

Advances in proton therapy will require appropriate access to a 100-250 MeV proton beam line for dosimetry studies, bench marking 3-D simulation codes, developing national calibration standards, and developing new beam scanning techniques. Synchrotron radiation-based coronary angiography will require the development of simpler light sources, with low capital and operating costs.

Opportunities for Cross-cutting Accelerator R&D

Accelerator R&D is currently carried out in support of the mission needs of the OER at national laboratories, universities, and in industry by researchers with interests directed towards a variety of potential applications. While the specific implementations and applications of accelerator technology may vary across the ER programs, in many instances the underlying accelerator physics concepts are shared. Examples which are relevant to the needs of a number of ER programs include:

- production and acceleration of high current ion beams
- production and acceleration of high brightness electron beams
- superconducting rf structures
- non-linear dynamics and optics
- beam stability and feedback
- storage ring quality magnets
- new superconducting materials
- novel lattices and beam optics
- high efficiency rf sources and accelerating structures
- beam polarization
- beam cooling
- targeting
- beam instrumentation and diagnostics
- beam control
- particle sources
- computer codes

This high degree of common interests provides important opportunities for both positive synergy and for the coordination of accelerator R&D activities within OER.